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DESIGN OPTIMIZATION OF A SINGLE-SIDED AXIAL FLUX PERMANENT MAGNET IN-WHEEL MOTOR WITH NON-OVERLAP CONCENTRATED WINDING

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Abstract. In this paper an iron core axial flux permanent magnet machine with a non-overlap concentrated winding is presented for in-wheel traction hub motor drives. The design and optimization is carried out for objectives of efficiency and power density. Torque ripple minimization is also investigated to determine the optimal magnet to pole pitch ratio. The result is a single-sided 16 kW, 340 Nm motor drive with open stator slots.

Key Words. Permanent Magnet, Axial Flux, Optimization, Non-Overlap Winding, Open Slot.

1. INTRODUCTION

Escalating energy problems facing the world have encouraged the pursuit for development of “green” alternative means of transport. Hybrid / electric vehicles are fast proving to be the promising alternative to the internal combustion vehicle. In contrast to replacing the combustion engine with an electric drive, in-wheel hub drives offer the additional advantages of removing all mechanical transmission / reduction gear and directly supplying energy to the wheel. Direct in wheel hub drives therefore increase efficiency, simplify layout, are adaptable to a wide range of vehicles, and are very attractive for automotive electronic stability programs (ESP) [1]-[3].

The unique pancake profile of axial flux machines has made them ideal candidates for in-wheel motor applications as they inherently match vehicle rim aspect ratios of large diameter and thin width. Figure 1 shows the expanded view of a single-sided axial flux permanent magnet (AFPM) machine. With the use of high energy permanent magnet (PM) material and non-overlap concentrated windings axial flux machines can achieve higher levels of efficiency and power density, ideal for limited space applications. By further utilizing open stator slots and pre-formed coils, the manufacture of these machines is also greatly simplified [1] [2].

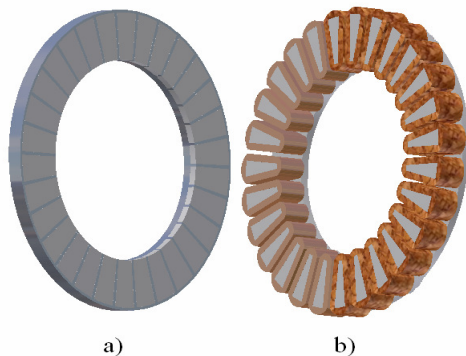


Fig. 1: Expanded View of a Axial Flux Machine a) rotor and b) stator with open slots.

In this work finite element (FE) based modelling is employed for the design. It is further used with conjunction of an optimization algorithm to obtain optimal machine designs. In section 2 the basic design choices considered and in section 3 the modelling and optimization, with later investigation into torque ripple and attraction forces.

2. DESIGN OBJECTIVES

2.1 Mechanical Aspects

The very initial choice with regard to in-wheel hub drives revolves upon the space available within the vehicle’s wheel and permissible machine mass. For a 15-inch rim, the maximum diameter calculated assuming 10mm end winding protrusion and clearance, is 330mm. Secondly the required performance of the motor drive must be chosen, this is done based on kinematical equations of vehicular motion [3]. In table 1 the main design criteria for the drive is outlined. The final design choices are with regard to mechanical construction, integration with the vehicle and safety. The motor drive should be mechanically robust, matched well to the wheel profile, sealed from the harsh environment, easily cooled, and easily serviceable. One important mechanical aspect with regard to AFPM machines pertains to the attraction forces between the stator and the rotor; in particular single-sided AFPM machines as they present the worse case. The forces and suitable bearing selection are given later in section 3.3.

Table 1. Design parameters

Outer Diameter	330 mm
Outer Width	< 70 mm
Mass	< 25 kg
Average torque	± 340 Nm
Current Density	< 11.5 A/mm ²
Base/Max Speed	450 / 1350 rpm

2.2 Electrical Aspects

The first design choice in concentrated non-overlap PM machines pertains to the pole-slot combination. Three main criteria influence this selection [4],

- 1) A high fundamental winding factor, since this is proportional to the flux linkage and thus torque,
- 2) A high lowest common multiple (LCM) as this equates to the cogging periods per cycle. The higher the cogging cycles the lower the magnitude,
- 3) A high greatest common divisor (GCD), as this describes the symmetry of the machine, the vibration modes and balancing forces.

The selection is not as simple as described above, as values often contradict, such as those with high LCMs having low GCDs etc. In addition machines with high LCMs do not always result in reduced cogging torque. Furthermore, reduced cogging torque does not always result in reduced torque ripple.

Incorporation of the machine within the wheel requires that it must inherently produce high torque at low speeds. The basic rule of thumb for a high torque low speed machine is that the number of poles be inversely proportional to the speed of rotation. On the basis of the previously outlined theory, several potential slot pole combinations can be identified. In this work a pole slot combination of 30 poles and 27 slots is selected, aspects for this topology and two additional examples are given in Table 2.

Table 2: Aspects of different machine topologies

N_p	N_s	k_{w1}	LCM	GCD
30	27	0.945	270	3
36	30	0.966	180	6
40	30	0.866	120	10

N_p denotes the number of poles, N_s the number of slots, and k_{w1} the fundamental winding factor. A double-layer winding is selected as opposed to a single-layer winding. Single-layer windings have proved superior with regard to insulation, self inductances, and fill factor, but in limited space applications, the large end windings they possess are disadvantageous and this is the main reason for the selection of a double-layer winding.

Open stator slots are selected primarily due to the ease of manufacture. Although open slot configurations generally lead to increased cogging torque and induced eddy current winding losses, the advantages in manufacture far outstretch the drawbacks. Additionally, certain pole-slot combinations, when used with open slots have reportedly reduced torque ripple pulsations [5] [6].

The air gap length for this machine is selected to be 1.6 mm; this is to allow for reasonable air gap flux density and mechanical clearance between the stator and the rotor. High energy fan shaped N40SH Neodymium Iron Boron (Nd-Fe-B) type magnets are selected for the rotor excitation, due to their high durability, temperature tolerance and coercivity of 923 000 A/m.

With the basic design choices in place, FE modelling is then employed to simulate and optimize the machine for best performance.

3. 2D FINITE ELEMENT MODELLING AND OPTIMIZATION

When modelling electrical machines, symmetry about the pole-slot combination (GCD) is normally used to reduce the model into a section with periodic boundary conditions. This simplifies the model and reduces simulation time required for the FE.

Axial flux machines taper in towards their inner centres and unlike radial flux machines, which have symmetry about their lengthwise cross section, axial flux machines present no symmetry. The only way to model these machines is by complete 3D modelling or by linearized 2D modelling shown in Figure 2.

Linearized 2D modelling is done based on the machine's average radius r_{avg} between the inner and outer radius. The width wise dimensions such of slots, teeth, magnets are all based upon the average radius and the model depth is taken as the active stack length. This modelling technique has been proved reliable and tremendously reduces solution time of the finite element model [7] [8].

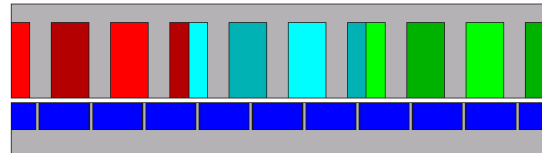


Fig. 2. Linear modelled section of 30 pole 27 slot AFPM machine.

With the machine modelled, a mesh is then generated on the model and nodal points are added. The magnetic vector potential on each nodal value is then computed by the FE analysis. Post processing is then used to translate the vector potentials to the desired values of flux linkages, torques, etc. The electromagnetic torque calculated in the FE analysis is given by

$$T_{ave} = \frac{3}{2} p (\lambda_d I_q - \lambda_q I_d), \quad (1)$$

where p is the number of pole pairs, I_d , I_q are the d-q axis currents, and λ_d , λ_q the d-q axis flux linkages.

3.1 Optimization

Electrical machine modelling is a highly non-linear process and trying to optimize machine parameters for example by graphing / tabulation is not efficient by any means. Optimisation algorithms based on Powell's method for example [8], provide a far superior method of searching for optimal points. Optimization is a point orientated process with which one must clearly state the design objective. The machine parameters to be optimised must also be clearly defined, as not to violate each other or their pre-defined range. Fixed parameters also have to be defined before the optimization; otherwise the objective will be unconstrained. Here the machine outer dimensions given in Table 1 are the fixed constraints. The objective function of the optimization is given by

$$F = y_{par} - \sum_{i=1}^2 w_i \varepsilon_i, \quad (2)$$

where y_{par} is the value to be maximised, ε_i the penalty functions, and w_i the respective weighting factors. The penalty functions are added to the objective function in order not to violate the limits of secondary functions such as less than average torque or higher than maximum current densities chosen for this case. Values of the penalty functions are given in Table 1, and are defined as

$$\varepsilon_1 = \begin{cases} (T_{min} - T_{ave})^2 & : T_{ave} < T_{min} \\ 0 & : T_{ave} \geq T_{min} \end{cases} \quad (3)$$

$$\varepsilon_2 = \begin{cases} (J - J_{max})^2 & : J > J_{max} \\ 0 & : J \leq J_{max} \end{cases}. \quad (4)$$

The selected machine parameters to be varied for the optimization are:

- r_i , machine inner radius,
- s_r , stator slot depth,
- s_y , stator yoke height,
- k_d , stator slot width to tooth width ratio,
- r_f , magnet to pole pitch ratio,
- r_m , magnet height and,
- r_t , rotor yoke thickness,

highlighted in Fig. 3.

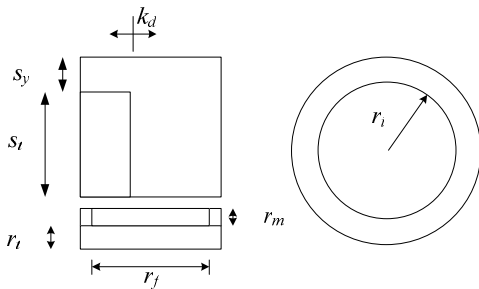


Fig. 3: Machine parameters varied in the optimization.

Two machine design objectives are pursued, namely:

- PM 1 : Efficiency ($T_{ave}/\text{copper losses}$),
- PM 2 : Power density ($T_{ave}/\text{total volume}$),

with results in table 3.

Table 3: Optimization Results

Variable	Min	Max	Optimal	
			PM 1	PM 2
r_i	0.05	0.14	0.06931	0.11251
s_r	0.02	0.04	0.03151	0.029
s_y	0.004	0.012	0.00591	0.006
k_d	0.3	0.8	0.5953	0.6329
r_f	0.7	0.96	0.94	0.94
r_m	0.004	0.012	0.00926	0.0106
r_t	0.004	0.012	0.00692	0.008
Torque [Nm]			400	340
Current density [A/mm ²]			8.88	10.23
Active volume [m ³]			0.003874	0.002517
Magnet mass [kg]			4.57	3.4
Total Mass [kg]			24.35	16.9
Power density [kW/m ³]			4875.8	6427.3
Attraction forces [kN]			20	13.8
Stack length [m]			0.096	0.0525
Diameter ratio			0.42	0.68

The efficiency optimization result (PM1) provides the best torque performance overall, exceeding the required 340 Nm. With regard to application, the result provides several drawbacks, mainly due to the large stack length which reflects upon the size and mass of the machine. In-wheel hub drives need to take up a small size within the vehicle rim so as to provide extra room for support structures and mechanical brakes. Excess un-sprung mass can lead to negative effects on vehicle dynamic handling and therefore must be kept minimal. Another drawback of the long active stack is that it aggravates the attraction forces (section 3.3). Finally the large resulting mass of PM1 reflects directly to cost, as it will require more material for construction.

The result of the power density based optimization (PM2) is constrained to the required torque of 340 Nm. The results yield a shorter stack length (45% reduction), and thus a lighter and more compact design with reduced attraction forces. The torque is lower by 15%, but this comes with a 35% lower volume, 31% lower mass and 31% less attraction force. Axial flux machines provide their highest power density levels at diameter ratios (*inner/outer diameter*) of around 0.6 - 0.7 [8] [9] [10] which closely agrees with the result of 0.68 found here. The higher current density of PM2 will also require additional cooling compared to PM1. It is also worth noting that PM2 requires a slightly higher magnet height to attain a high power density level. With the majority of advantages in support of power density

based PM2, it is therefore selected as the superior candidate.

3.2 Torque Quality

Torque production in an electrical machine is not entirely smooth; it contains pulsations known as *torque ripple*. Torque ripple comes about from the permeance variations in the air gap due to the slotting effect (cogging), harmonics in the magneto motive force (MMF), harmonics in current from inverters and saturation in the magnetic circuit of the machine [11]. When torque ripple is minimized, this leads to reduced vibration and longer machine life, along with smooth and quiet operation. The instantaneous torque of an electrical machine can be calculated by the co-energy method given by

$$F_s = \frac{dW'}{ds} \cdot r_{avg} \approx \frac{\Delta W'}{\Delta s} \cdot r_{avg}. \quad (5)$$

Where W' is the magnetic co-energy, and s some small displacement.

In order to obtain smooth torque production there are several methods available [6] [9]. In the case of AFPM open slot double-layer machines, variation of the magnet to pole pitch is most practical, simple and the least costly. The peak to peak torque ripple is calculated with incremental stepping of the machine in small increments up to one cycle of 60 electrical degrees, and repeated for different values of magnet to pole pitch ratios as given in Figure 4. Coincidentally for this case, the magnet to pole pitch ratio is at the optimum from the optimization and requires no further adjustment. Figure 5 shows the instantaneous torque waveform at the magnet to pole pitch ratio of 0.94.

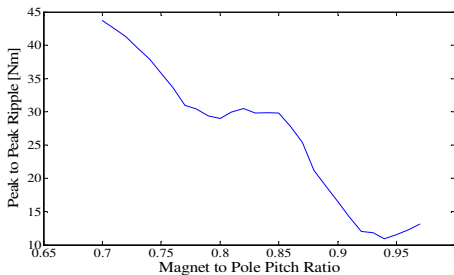


Fig. 4: Peak to peak ripple torque with magnet to pole pitch ratio, minimum 11.2 Nm (3.3 % of average) at 0.94.

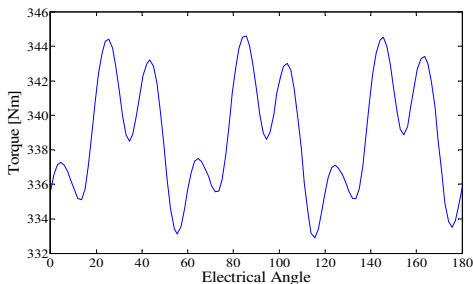


Fig. 5: Instantaneous torque waveform at magnet to pole pitch ratio of 0.94.

3.3 Attraction Forces

All AFPM machines suffer from axial attraction forces between machine parts, predominantly so in single-sided machines. The attraction force is directly proportional to the active machine area and stack length, which are inversely proportional to the diameter ratio. The attraction force is given by,

$$A_F = \frac{B_g^2 S_m \alpha_m}{2\mu_0} \quad (6)$$

where A_F is the attraction force, B_g the flux density in the airgap, S_m the airgap surface area, α_m the percentage of magnet to airgap area, and μ_0 the permeability of free space.

From the analysis, an attraction force of $A_F = 13.8$ kN is calculated for PM2. Care must be taken in the resultant bending in the rotor back yoke (Δ_r) and the stator back support (Δ_b) depicted in figure 6. Finite element analysis is once again used to determine the maximum deflection in both structures so as not to violate the mechanical clearance. The maximum combined reduction in clearance is calculated to be 0.0637 mm (4.5%) which is within acceptable limits. A set of paired back-to-back taper roller bearings is selected to handle the force.

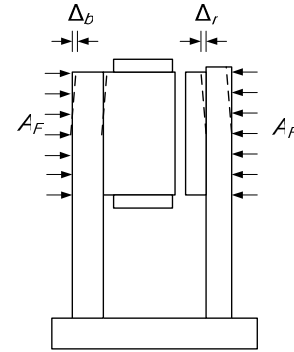


Fig. 6: Deflection in rotor disk and stator back support.

4. CONCLUSION

The basic design procedures and optimization are highlighted for an in-wheel axial flux permanent magnet hub drive. The optimization showed how the machine can be optimized for either maximum torque or maximum power density subject to prescribed constraints. Within the fixed volume, a maximum of 400 Nm is available with efficiency based optimization, but when optimized for power density, a light weight and compact machine with a short stack length is derived. Based on the power density optimization for the required 340 Nm, torque is 15% lower than the efficiency based optimization, but this is well justified by the reduction in volume of 35% and mass of 35%, which will lead to reduced costs. Torque ripple reduction of the topology is investigated, and a low value of 3.3 % peak to peak is

obtained. Single sided open slot double layer non overlap AFPM machines, are thus excellent candidates for in-wheel traction applications.

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